An Energy-Efficient Media Access Control Protocol for Chain-Type Wireless Sensor Networks*

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ABSTRACT

We present in this paper an energy efficient media access control (MAC) protocol for chain-type wireless sensor networks. The chain-type sensor networks are fundamentally different from traditional sensor networks in that the sensor nodes in this class of networks are deployed along narrow and elongated geographical areas and form a chain-type topology. Recently, we have successfully developed hierarchical network architecture, sensor deployment strategy, and corresponding network initialization and operation protocols for this class of sensor networks [1]. In this paper, we present a novel TDMA scheduling protocol that takes full advantages of the available channel reuse inherent in the chain-type sensor networks to develop energy efficient and high data throughput MAC protocols for sensor data transmission. The synchronized TDMA scheduling allows the nodes to power on only when it is scheduled to send and receive and therefore results in additional energy saving. Within a cluster, parallel transmission is made possible because of the linear distribution of nodes within the chain-type topology and this yields the desired high throughput. Preliminary simulations have been carried out to show that the proposed TDMA scheduling outperforms the well-known SMAC scheme in terms of energy efficiency and data throughput under various duty cycles.

Keywords: wireless sensor networks, chain-type topology, energy efficiency, TDMA scheduling, MAC protocols, channel reuse, networking protocols, high network throughput

1. INTRODUCTION

Recent advances in MEMS, low power radio, pervasive computing technology, and wireless networking have led to rapid development of wireless sensor networks. Significant research has been carried out to investigate various technical challenges in wireless sensor networks. These technical challenges include low-power signal processing [2,], power-aware media access control[3,4,5,] energy-aware data aggregation and routing [6,7,8,9,10,11,12,13,14,15], topology management [16,17], localization [18], synchronization [19,20], and collaborative signal and information processing [21,22,23,24]. Among these research efforts, the central theme shared by these approaches is the issue of energy efficiency for designing and implementing various components of a wireless sensor networks, including sensing, signal processing, data routing and networking, radio communication, and power management.

One of the key technologies in wireless sensor networks is the MAC protocols that are needed to enable seamless operations of a sensor network for data collection from the sensor nodes and data transmission to the data sink [3,4,5]. Unlike the traditional wireless networking, energy efficiency and scalability are two major attributes of a MAC protocol for a wireless sensor network. This is because the wireless sensor networks are usually battery powered with severe energy consumption constraint and a sensor network usually consists of large number of sensor nodes deployed densely within a concentrated area.

Numerous existing wireless sensor networks have been developed to extend our ability to monitor and control the physical world, including biological and environmental monitoring tasks, ranging from marine to soil and atmospheric context [25,26,27], and defense and homeland security applications, ranging from target detection, classification, to object tracking, and intrusion detection [21,22,23,24,28,29,30]. These systems usually assume that sensor nodes are deployed in a distributive fashion within a relatively concentrated two dimensional or even three dimensional regions of interest. Some of them further assume that each node in a sensor network has the ability to transmit data to any other sensor node or directly to the base station [10,11]. Existing MAC protocols developed for wireless sensor networks are also based on these assumptions to design energy efficient MAC protocols for sensor data communications.

However, these existing schemes are not applicable to a class of critical sensor network applications in which the sensor nodes are strategically deployed with **chain-type topology** along a relatively long range of distance. This class of

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applications is often limited by their natural formation of landscape or manmade infrastructures of long ranges, such as rivers, coastal lines, highways, and national land borders. The geographical nature of these premises demands that the deployment of the sensor nodes be restricted to the long stretch of narrow and elongated spreading.

It is true that the chain-type wireless sensor networks under consideration in this research share many inherent characteristics of general wireless sensor networks since such networks also consist of a large number of unattended sensor nodes in harsh environments. The chain-type sensor networks also operate under severe resource constraints, including restricted energy supply, low bandwidth, scarce computational power, and limited communication capability.

However, their unique chain-type topology and their usually deliberate deployment at strategic locations along the infrastructure of interest make these networks more restrictive in terms of inter node communication, sensor data aggregation, and seamless flow of sensing data and control commands. These additional restrictions pose a new set of technical challenges that is different from those in the existing sensor networks.

One major challenge for such chain-type sensor networks is to develop an energy efficient communication protocols for the sensor nodes to communicate with each other and with the data sink of the wireless sensor network. Because of the unique chain-type topology, the radio communications between sensor nodes are limited by directional transmission along the path of chain-type sensor node distributions. The success of these MAC protocols will determine how seamlessly such a sensor network operates and how efficiently the chained sensor nodes will coordinate the data transmission within a cluster of sensor nodes and with the remote data sink.

In this paper, we will present an energy efficient media access control (MAC) protocol for chain-type wireless sensor networks. This MAC protocol is a set of novel TDMA scheduling protocols that takes full advantage of the channel reuse inherent in the chain-type topology to develop energy efficient and high data throughput MAC protocol for sensor data transmission. The synchronized TDMA scheduling allows the nodes to power on only when it is scheduled to send and receive; hence results in extra energy saving. Within a cluster of nodes, parallel transmission is made possible because of the linear distribution of the nodes within the chain-type topology and yields the desired high throughput.

The rest of this paper is organized as follows. Section 2 reviews existing schemes of MAC protocols for sensor networks. Section 3 presents an overview of the hierarchical network architecture, sensor deployment strategy, and corresponding network initialization and operation protocols that have been developed for the unique chain-type wireless sensor networks. Section 4 describes in detail the proposed energy efficient TDMA scheduling scheme for the chain-type sensor networks. We will show how to use the channel reuse inherent in chain-type sensor networks to achieve parallel transmission of sensor data along the direction of sensor node chains. Section 5 presents the results of simulation based on the proposed TDMA scheduling. We show that the proposed TDMA scheduling is able to outperform the well-know SMAC scheme in terms of energy efficiency and data throughput under various duty cycles.

2. EXISITNG SCHEMES OF MAC PROTOCOLS

Energy efficiency is the core of the MAC protocol design for wireless sensor networks. An excellent analysis of how the energy is wasted during the execution of the MAC protocols has been presented in a recent paper by Ye, Heidemann, and Estrin [3]. In this paper, it is claimed that the energy is wasted mainly in four aspects: idle listening, collision, overhearing, and protocol overhead. Idle listening is due to a typical working cycle of a sensor network in which the nodes will be in idle state for long time if nothing is sensed. Measurements have shown that idle listening consumes about 50%~100% of that by receiving. Collisions occur when two nodes transmit simultaneously and interfere with each other's transmission. The data packets are corrupted and discarded, and the subsequent re-transmission is required which increases energy consumption. Overhearing refers to the case when a node receives data packets that are destined to other nodes. This can be simply avoided by turning off its radio on such occasions. Protocol overhead is necessary to establish the radio communication through control packets (RTS/CTS/ACK). The protocol overhead does not contain sensor data but consumes additional energy.

Current MAC protocols developed for sensor networks seek different approaches to solve these four problems in energy wasting. They can be broadly divided into contention-based [3,31] and TDMA [8,32] MAC protocols.

IEEE 802.11 distributed coordination function (DCF) [33] is a standardized contention-based protocol which is based on carrier sensing multiple access (CSMA) and collision avoidance (CA). CSMA is implemented by both virtual and physical carrier sensing, and CA is achieved through RTS/CTS handshake of the MACAW protocol [19]. CSMA/CA in 802.11 effectively reduces collisions in multi-hop ad hoc networks. In addition, the DCF supports power saving mechanism (PSM), which further reduces the energy wasted in continued idle listening by adopting periodical listening. However, PSM in the DCF is only supported in single-hop ad hoc networks. Tseng [34] improved the PSM in multi-hop networks. Singh proposed the PAMAS [35] which reduces the energy wasted in overhearing by shutting off the radio for a duration indicated by the RTS/CTS packets of neighboring nodes. Ye *et al* and van Dam *et al* proposed the S-MAC [3] and

T-MAC[31], respectively, which integrate the coordinated periodical listen, overhearing avoidance [35] and CSMA/CA [33] to reduce the energy wasted in idle listening, overhearing and collisions. In contrast, the TDMA scheme proposed in this paper will completely eliminate the overhearing and collisions, and reduce the idle listening to a minimum level.

TDMA MAC protocols are inherently collision free. LEACH [8] and Bluetooth [36] are TDMA protocols which use a cluster head to schedule the single hop communications within a cluster. In comparison, our scheme is to schedule the multi hop communication that has been selected as the mode of communication for cluster heads in the chain-type sensor networks. LEACH allows the frame size to change with the number of sensor nodes in a cluster, while Bluetooth fixes the frame size to accommodate at most 8 nodes, which however limit their scalability. Arisha [32] partitions the network into large clusters. In each cluster, a gateway node schedules the multi-hop communications between sensor nodes and the gateway node. The TDMA schedule is based on the information of the sensor nodes' energy level, traffic load and so on, which are reported periodically from each node to the gateway nodes through single hop communications. This scheme is not applicable to chain-type sensor networks since this will result in significant energy consumption and the requirement of high radio capability of each node distributed along an elongated chain-type network as will be discussed in Section 3.2. Furthermore, the fixed length frame must be designed to accommodate the largest number of nodes within a cluster. Clearly, both strategies limit the scalability for chain-type sensor networks and therefore are not applicable.

3. OVERVIEW OF THE CHAIN-TYPE WIRELESS SENSOR NETWORKS

3.1. The New Hierarchical Chain-Type Architecture

We have developed an innovative multiple tiered hierarchical network architecture for the chain-type long range wireless sensor networks [1]. The first consideration for the proposed hierarchical architecture is scalability for this unique class of sensor networks. We base our investigation on a three-tier hierarchical architecture. The lowest tier consists of common sensor nodes which are grouped into clusters at designated strategic sites along an elongated chain-type area. Each cluster has a cluster head node (CHN) with enhanced capabilities. All CHNs form the second tier. The third tier consists of the base stations (BSs). The SNs perform data sensing task and report to local CHNs. CHNs aggregate the data streams from the related SNs and then forward the aggregated local-view data stream to a BS.

It is clear that such hierarchical architecture can be easily expanded to include more BSs in the highest tier for a long range chain-type sensor networks. Additional tiers can also be added between CHNs and BSs based on specific application needs. Therefore, the proposed architecture is easily scalable to increase the size of the network. In this case, the size of the network corresponds to the length of an elongated topology.

Figure 1 illustrates the architecture of a three-tier chain-type wireless sensor network. Without loss of generality, we assume in our analysis that there is only one BS which is without energy constraint, and that both SNs and CHNs are battery-powered. However, we assume that the CHNs are equipped with higher capability in both computation and communication and that the nodes of the same type (CHNs or SNs) are homogeneous (equal capability).

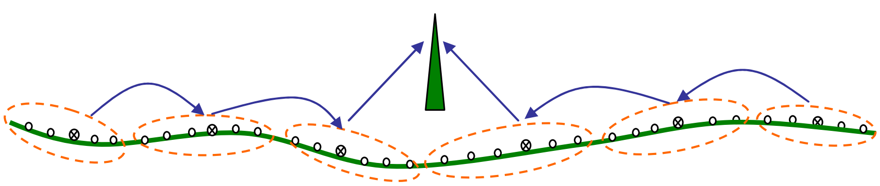

Fig.1 The architecture of chain-type wireless sensor network

3.2. Communication Mode Selection and Smart Cluster Head Deployment

The study of the network architecture concludes that the proposed hierarchical architecture is scalable for chain-type wireless sensor networks [1]. The study also concludes that the communication and networking between CHNs and BS is the key to the development of energy efficient operations that would maximize the life time of the sensor networks [1]. Since there are essentially three possible modes of communication between CHNs and BS: single-hop, multi-hop, and hybrid, we need to select an appropriate mode of communication in order to balance between energy consumption and communication performance. We have concluded that the multi-hop communication is most appropriate for the chain-type sensor networks and have also developed a load balancing smart deployment strategy to match with the multi-hop communication so as to maximize the lifetime of the chain-type sensor networks.

3.2.1 Selection of Communication Modes based on Energy Performance Tradeoff

The selection of communication modes has been based on the abstract network topology of CHNs and BS shown in Figure 2 with ideally deployed locations of $2N$ CHNs that are R meters apart.

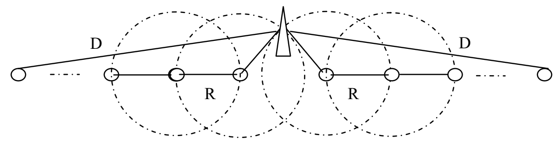

Figure 2. Topology of chain-type wireless sensor network

In the case of single hop communication mode, all CHNs communicate with the BS directly. The critical CHN that determines the network lifetime is the remotest one from the BS. According to energy model we adopted in developing network architecture [9], we showed that [1] the energy expenditure in single hop mode increases with the 4th power of the number of hops N at the given radio range R. Similarly, we have also showed that [1] the energy expenditure in multi-hop mode increased only linearly with the number of hops N at the given radio range R. For hybrid mode, when the communication modes switch between single hop and multi-hop based on the minimum energy rules, it has been shown that there exists an optimal percentage of switching that will minimize the overall energy consumption [1].

The hybrid communication mode is useful for some sensor network applications when the distance between the hops is relatively short [13]. However, in a typical application scenario for the chain-type sensor networks, the distance between the CHNs R is in the range of 100 to 1000 meters. With such assumption, we showed that the energy consumption for hybrid mode is virtually the same as the multi-hop mode. After considering the manufacturing cost of radio electronics for switching between single hop and multi-hop for hybrid communication, we concluded that multi-hop communication mode is most appropriate for the chain-type sensor networks to achieve the optimal energy-performance tradeoff [1].

3.2.2 Smart Cluster Head Deployment with Multi-hop Communication Mode

One problem associated with the multi-hop communication mode is the uneven energy consumption for CHNs from different clusters. The CHN closest to the BS will die first because of its heaviest burden in relaying data transmission for other CHNs. The lifetime of this CHN shall determine the lifetime of the entire group of the CHNs served by the same BS. Likewise, the CHN next to this CHN will endure second heaviest burden in relaying data transmission and shall die next. We solve this problem by developing a smart strategy of deploying CHNs in order to balance the extra burden of relaying for some CHNs. This snart strategy calls to deploy redundant CHNs at clusters closer to BS to balance the energy consumption in multi-hop communication mode. With unequal number of redundant CHNs, those clusters that support more relay tasks shall have proportional increase in their battery lifetime.

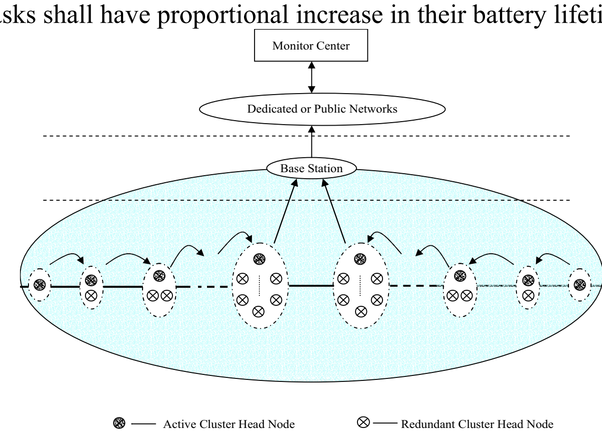

Figure 3. Illustration of Smart Sensor Node (CHNs) deployment.

For M clusters uniformly located along the chain-type area, we proposed to deploy linearly $\{M, M-1, \cdots, 1\}$ CHNs at clusters from the closest to the farthest, so that each CHN shares approximately the same load and all clusters run out of energy at about the same time. The details of this **smart cluster head deployment** strategy is reported in a separate paper [1]. Figure 3 illustrates this smart sensor node deployment strategy with **redundant CHNs** at locations closer to BS to balance the uneven transmission load.

3.3. Networking Protocols

In this section, we first propose a set of network protocols serving as a unified framework for the time-driven chain-type large scale sensor networks. In the time-driven multi-hop sensor networks, each SN sends data periodically to its CHN, and then, CHN aggregates multiple data streams and forward the aggregated data stream to BS in a multi-hop fashion. We will extend the protocols to query-driven and event-driven applications. In these cases, sensor data are sent to BS only when a query is received or an event is triggered.

Figure 7 shows the operations of the network in time sequence. It first runs an initialization phase when the network is self-organized. Then it runs periodically the normal operation phase when sensor data collection occurs.

3.3.1 Initialization Stage

In the initialization phase, the network accomplishes the network synchronization, self-organization of CHNs, self-organization of SNs, and routing table establishment. The protocols in this phase consist of following steps:

Step 1: *Synchronization* - Each BS broadcasts beacons including synchronization and other network information. All SNs and CHNs within a BS's coverage area synchronize with it. All BSs may be synchronized through GPS;

Step 2: *Self-organization of CHNs* - Each CHN broadcasts its own ID and other capability information. From the receiving signal's level, a CHN is able to identify all intra-cluster CHNs (redundant CHNs). Then they shall elect one as the active CHN. In this research, we propose a simple scheme based on the value of the CHNs' ID. A CHN sets up a table which contains the ordered IDs of all the intra-cluster CHNs. The active CHN is elected from this ordered table according to a specific rule. For example, we can set a top-down rule which chooses a CHN as the active one in the order from the highest ID value to the lowest. In addition, each active CHN knows its unique cluster ID and use that for route discovering later. It can either be assigned by the BS, or just be set as the highest ID value of CHN according to that ordered table. Contention-based MAC protocols are used in this phase.

Step 3: *Self-organization of SNs* – Each active CHN broadcasts beacons within its coverage. A SN associates itself to a CHN from which it receives the highest signal power. After a short period, the active CHN collects all the information of its associated SNs. Contention-based MAC protocols are used in this phase.

Step 4: *Routing Table Establishment* - Each active CHN initiates a routing discovering procedure. For a chain type network, as it can be represented well by a linear array network, it is easy for each CHN to obtain a routing table, from which it knows all of its upstream and downstream CHNs. It is important to note that the source and destination addresses include cluster IDs. This routing table will be updated during normal operation stage according to the specific routing algorithms employed. Each active CHN broadcasts the routing information so that non-active CHNs store this information in their own memory. After this, all non-active CHNs switch to sleep mode. Contention-based MAC protocols are used in this phase.

3.3.2 Normal Stage

In normal stage, the network runs in periodic rounds of data collection. Each round of the network protocol includes following steps:

Step 1: *Synchronization* - All CHNs wake up from sleep mode and synchronize with the base station, which periodically sends out the beacons at the beginning of each round. Then each CHN updates its round counter;

Step 2: *Active CHN update* – The active CHN broadcasts "active CHN update" information when its residual energy below a preset threshold, i.e. 5% of its initial energy. Then the CHN having the closest ID value to that of the active CHN becomes new active CHN from this round on. All other CHNs switch into sleep mode until next round;

Step 3: *Data sensing and communicating within cluster*– Each active CHN manages data sensing and communication task of the SNs and performs data aggregation task within the cluster. Either scheduled MAC protocols or contention-based MAC protocols can be used in this stage.

Step 4: *Data communicating between clusters*– Each active CHN transmits the aggregated data multi-hop to BS. During this phase scheduled MAC protocols or contention-based MAC protocols can be used. For scheduled MAC protocols, it is BS that assigns the sequence of transmissions. For contention-based MAC protocols, they are expected to combat the problems of hidden terminal and exposed terminal and incorporate the sleep mode operation to achieve better energy efficiency. An active CHN will not switch to sleep mode until it has transmitted its own packet and relayed all loads of its downstream nodes. Therefore, different CHNs have different length of sleep time according to the total data load and the adopted MAC protocol.

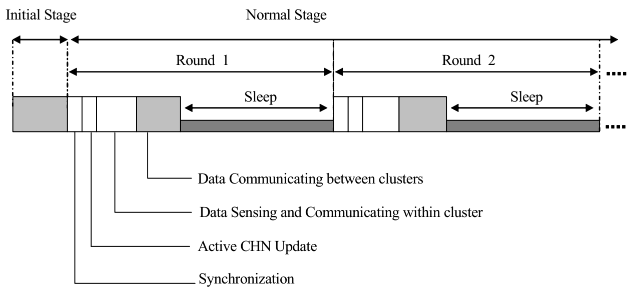

Figure 7 Time sequence of operations of network protocols for chain-type sensor network

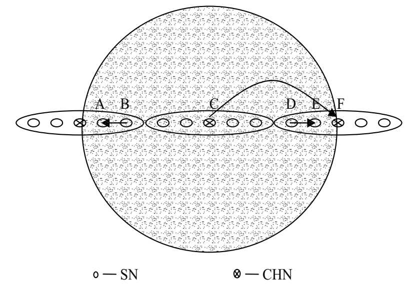

Figure 8: Interactions between intra- and inter-cluster communications

3.3.3 Extension to Query-Driven and Event-Driven Applications

For query-driven and event-driven applications, intra-cluster and inter-cluster communications may occur simultaneously due to the lack of coherent time scheduling. This may cause collision between intra- and inter-cluster communications. Fig. 8 shows an example of the interactions between the intra-cluster and inter-cluster communications. On one hand, if multiple short range intra-cluster communications starts first, say, B and D are sending data to A and E respectively, C can not hear their transmission and may start sending date to E. Then, all on-going intra-cluster communications within the shadow area will collide and retransmissions are required. This leads to more energy waste. On the other hand, if long range inter-cluster communication C to F starts first, then all intra-cluster communications within the shadow area will be restricted, which leads to longer latency.

To achieve better energy efficiency and latency, we need to decouple the interactions between intra and inter communications. We propose to separate the intra- and inter-cluster communications into two distinct frequency channels 1 and 2 as shown in Fig. 9, so that they do not interact with each other. The reason code division channels is not suitable is because the significant "Near-Far" effect [37] for the chain-type topology. This will lead to worse bit error rate and waste of retransmission energy. Fig. 9 shows the time sequence of network protocols suitable for all three types of applications in normal operation stage. One disadvantage of this protocol is that each CHN must have two radios equipped. In the case of time-driven (scheduled) applications, there is no need for CHNs to have two radios. However, for all three types of applications, SNs require only one radio.

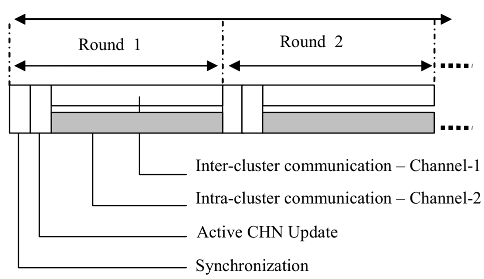

Figure 9: Time sequence of network protocols for all applications

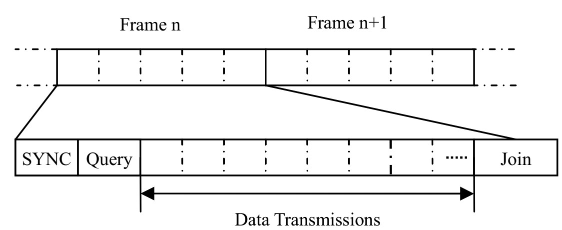

Figure 10. TDMA frame structure

4. THE PROPOSED TDMA SCHEDULING PROTOCOLS

The proposed TDMA scheduling protocols are explicitly developed for the chain-type sensor networks to take full use of the available channel reuse inherent in the chain-type sensor networks. We aim at developing an energy efficient and high throughput scheme for data transmission within the chain-type sensor networks. The synchronized TDMA scheduling allows the nodes to power on only when it is scheduled to send and receive and therefore results in additional energy saving. Within a cluster, parallel transmission is made possible because of the linear distribution of nodes within the chain-type topology and this yields the desired high throughput. Notice that only chain-type hierarchical architecture is able to facilitate such an energy efficient and high throughput TDMA scheduling.

To be consistent with the hierarchical architecture, sensor node deployment, and network initialization of the chain-type sensor networks as we described in Section 3, we make the following assumptions on the network model in order to introduce the proposed TDMA scheduling schemes:

1. An N-1 hop chain topology of a wireless sensor network shall consist of N nodes. The Nth node is the scheduling node like CHN as shown in Figure 1. Each node is equipped with single half-duplex transceiver. Scheduling node has large radio range to reach all of its associated nodes, whereas, non-scheduling nodes are only capable of covering one hop distance. Namely, both the communication range and interference range are equal to one hop of distance.
2. Each node has a unique sequential index number {1, 2, 3, … , N}, which can be obtained during the network initialization stage or during the network operation stage. Each node also has the knowledge of the number of data transmission slots a frame contains, which is either preset or obtained in the network initialization stage.

Figure 10 shows the frame structure of the proposed TDMA scheduling protocol. Each frame consists of four sub-fields: Synchronization, Query, Data Transmission, and Join. During the Synchronization period, the scheduling node broadcasts the beacon signal to synchronize all associated nodes. During the Query period, the sink node may send out query or other control information to all nodes. The Data Transmission period consists of several slots, during each slot there may be multiple *autonomously* scheduled transmissions. The scheduling of simultaneous transmissions makes full use of the chain-type topology and will be explained in detail next. The Join period is for new members that may be added to the group.

Note that the proposed TDMA scheduling protocol does not require the scheduling node to obtain information on energy level, traffic load or transmission requests, neither does it arrange any scheduling task during operation time as in some the existing schemes [8,32]. The scheduling node is only used to assign each node a unique sequential index number during the network initialization stage and broadcast query or other information during operation stage. Once a node has this unique index number, it will *autonomously* schedule its own transmission and reception without affecting other nodes' operation.

We consider TDMA scheduling for both unidirectional and bidirectional transmission cases. The unidirectional case is for node-to-sink communications such as data gathering while the bidirectional case is for local broadcast communications such as collaborative signal and information processing. To accommodate the flexibility in employing either frequency channel or code channel, we will develop the corresponding scheduling schemes for both cases.

4.1. Unidirectional TDMA scheduling

In unidirectional communication pattern, all nodes report their data multi-hop to the scheduler node or sink node (CHN). We first describe the scheduling scheme for the frequency channel then proceed to the code channel.

4.1.1 The scheduling rule for frequency channel

The scheduling rule for frequency channel consists of the following three steps in each frame:

Step 1: Initialize the slot index number $slot\_id$ =0 and node index number $node\_id$ =0;

Step 2: Choose nodes whose index number match $\{(node\_id + freq\_reuse\_factor \times m) < N, m = 0,1,2...\}$ as the senders, where in this case the parameter $freq\_reuse\_factor = 3$ and nodes whose index number match $\{(node\_id + freq\_reuse\_factor \times m + 1) \le N, m = 0,1,2...\}$ as the corresponding receivers in the current slot of operation;

Step 3: Increase the count $slot\_id$ +1. Check the value of the $slot\_id$. If $(slot\_id = slot\_id\_\max)$, then, stop. The parameter $slot\_id\_\max$ is the maximum number of data transmission slots a frame contains. If ($slot\_id$ mod $freq\_reuse\_factor$)=0, then, set $node\_id = 0$, and go to Step 2. Otherwise, update $node\_id$ +1, then, go to Step 2.

We use a 10-node local cluster of a chain-type sensor network to explain this scheduling rule. Node 9 is assumed as the sink node or CHN. For frequency channel, the chain-type topology results in reuse factor of 3. Therefore, nodes that are $3R$ away can simultaneously transmit without interference. Table 1 shows the scheduling rules of the first four slots. In slot 0, nodes 0, 3, 6 transmit data to nodes 1, 4, 7 respectively. In this case, each node is able to send out data again after 3 slots. From the fourth slot, it repeats the transmission pattern of the first slot. In fact, for the *ith* slot, $i = 0,1,2,...$, it always repeats the transmission pattern of slot (i mod 3). Therefore, a chain-type network with N ($N \in [4, \infty]$) nodes, has just three transmission patterns. In each slot there are always $\lfloor N/3 \rfloor$ pairs of parallel transmissions. This fully exploits the frequency channel reuse and results significantly enhanced data throughput.

Notice that the proposed TDMA scheduling scheme is independent of the number N. It is therefore scalable to large size chain-type sensor networks. The above scheduling scheme is also an *autonomous* scheduling scheme. It has the following property that it does not require the scheduling node or the CHN to schedule other nodes time wise when and how long to transmit or receive. Instead, each node schedules itself with the only knowledge of its index number $node\_id$ and the number of data transmission slots a frame contains： $slot\_id\_\max$. On one hand, this property will simplify the TDMA scheduling protocol and thus save energy, because a lot of signaling overhead such as energy level, traffic load etc. is no longer necessary. On the other hand, this may lead to energy waste when duty cycle is low, because a node will always keep active in its scheduled slot even it has completed the data transmission or reception during the given time slot.

To remedy this drawback, we develop an energy conserving method which can be easily integrated into the proposed scheduling scheme. In each slot, the scheduled active nodes shall shut off their radios if they have no data to send. The scheduled receiving nodes shall measure their carrier signals for a very short interval (in microsecond scale), like DIFS_Time of 802.11 DCF mode [33]. If there is no incoming signal detected, they shut off their radios immediately. As a result, under low traffic load, it achieves high energy-efficiency by reducing the idle listening to a very low level. Under high traffic load, it achieves higher throughput by pipelining the maximum number of parallel transmissions that do not interfere with each other, while maintaining high energy-efficiency because it completely eliminates the collisions and overhearing.

4.1.2 The scheduling rule for code channel

The proposed TDMA scheduling can also be applied to cases when the radio channel is a code channel. In a multi-hop chain-type sensor network, it is not necessary to assign each node a unique code channel. Instead, the same code channel can be reused for sensor nodes that are two hops away. Hence, we can use just three codes for a chain-type network since such a code assignment can be scalable to networks with any number of nodes.

The scheduling rule for code channel also consists of the three steps as described in frequency channel case. The only difference lies in the step 2 and step 3, where we need to replace the parameter $freq\_reuse\_factor = 3$ with $code\_reuse\_factor = 2$. For simplicity of presentation, the details of the procedures shall not be described.

Table 2 shows the scheduling information of the first four slots for a 10 node chain-type network. After two slots, each node is able to send out data once. Note that a chain-type network using code channels has just two transmission patterns which fully exploit the channel reuse. Within each slot, there are always $\lfloor N/2 \rfloor$ pairs of parallel transmissions.

4.2. Bi-directional TDMA scheduling

In bidirectional communication pattern, nodes exchange data with their neighbors to accomplish some specific tasks such as collaborative information and signal processing. A simple solution will be to adopt the unidirectional scheduling schemes and change the flow direction alternatively. The scheduling node will control the flow direction in Query broadcast. However, a more efficient scheme of true bidirectional transmission will be developed, again by making full use of chain-type topology, in order to achieve even higher throughput performance.

The principle of such true bidirectional scheduling is to set up one-way parallel transmissions that take place every four hops away. The bi-direction scheduling rule for frequency channel will consist of the following four steps in each frame:

Step 1: Initialize the slot index number $slot\_id$ =0 and node index number $node\_id$ =0;

Step 2: For direction-1, choose nodes whose index number match $\{(node\_id + 4m) < N, m = 0,1,2...\}$ as senders and nodes $\{(node\_id + 4m + 1) \le N, m = 0,1,2...\}$ as the corresponding receivers in the current slot.

Step 3: For direction-2, choose nodes whose index number match $\{(node\_id + 4m + 3) \le N, m = 0,1,2...\}$ as senders and nodes $\{(node\_id + 4m + 2) < N, m = 0,1,2...\}$ as the corresponding receivers in the current slot;

Step 4: Increase the count $slot\_id$ +1. Check the value of the $slot\_id$. If $(slot\_id = slot\_id\_\max)$, then, stop. The parameter $slot\_id\_\max$ is the maximum number of data transmission slots a frame contains. If ($slot\_id$ mod 4)=0, then, set $node\_id = 0$, go to Step 2. Otherwise, update $node\_id$ +1, go to Step 2.

Table 3 shows such scheduling rules for the first five slots for a 10 node cluster within a chain-type network. Here, node 9 and node 0 are assumed to be the sink node of direction 1 and direction 2, respectively. After four slots, each node is able to send one data in both directions. From the fifth slot on, it shall repeat the transmission pattern of the first slot. Hence, for the *ith* slot, the transmission repeats the pattern of slot (i mod 4). Note that there will always be N/2 or N/2-1 pairs of parallel transmissions in a slot. If we adopt the unidirectional scheme directly, there will be only $\lfloor N/3 \rfloor$ pairs for each slot of transmission.

When the code channel is adopted by the sensor networks, the scheduling rule for code channel can be the same as that for frequency channel. A simple alternative can also be developed. Table 4 shows one of those examples.

Table 1. Frequency channel (uni-direction)

Slot	Sender
0	0, 3, 6
1	1, 4, 7
2	2, 5, 8
3	3, 6, 0

Table 2. Code channel (uni-direction)

Slot	Sender
0	0, 2, 4 , 6, 8
1	1, 3, 5, 7
2	2, 4, 6, 8, 0
3	3, 5, 7, 1

Table 3. Freq./Code channel (Bi-direction)

Slot	Sender	
	Dir-1	Dir-2
0	0, 4, 8	3, 7
1	1, 5	4, 8
2	2, 6	5, 9, 1
3	3, 7	6, 2
4	4, 8, 0	7, 3

Table 4. Code channel (Bi-direction)

Slot	Sender	
	Dir-1	Dir-2
0	0, 2, 4, 6, 8	
1	1, 3, 5, 7	
2		9, 7, 5, 3, 1
3		8, 6, 4, 2
4	2, 4, 6, 8, 0	

4.3. Analysis of the Proposed TDMA Scheduling Protocols

From the scheduling examples shown in Sections 4.2.1 and 4.2.2, it is clear that the proposed scheduling protocols are energy efficient and with high throughput. The energy efficiency comes from the synchronization of the sensor nodes to allow the sensor nodes to power off when it is not scheduled to send and receive. Such synchronized data transmission also eliminates the possibility for collision which has been identified as major source of energy waste. The high throughput comes from the parallelism of the data transmission resulting directly from our explicit exploitation of the unique chain-type topology of such sensor networks. In addition, the proposed TDMA scheduling protocols also have the following characteristics.

First, the above bi-directional scheduling scheme provides the fairness to the communications in both directions. In practical sensor network, there might be a predominating communication pattern, e.g., communications in direction-1 dominate over direction-2. In such case, more slots may be wasted in direction-2 communications. To remedy this, we can adjust the time allocations for unidirectional and bidirectional communications according to practical needs. For example, we can assign more frames to work in unidirectional communications, and less frames to work in bidirectional communications. The communication pattern of the current frame can be announced in the query broadcast period.

Second, as the unidirectional scheduling repeats the transmission pattern every 3 slots and the bidirectional scheduling repeats every 4 slots, we can design each frame consists of m*12 slots, m=1,2,… In this case, the exact frame length will depend on the network traffic load and latency requirement. Thus for a frame of 12 slots, the unidirectional scheduling will enable the sink nodes to receive 4 data packets, while the bidirectional scheduling will allow the sink nodes to receive 6 data packets in both directions.

Finally, in order to guarantee data delivery in MAC layer, an ACK packet should be returned from the receiver to the sender. Such mechanism will not cause collisions in the case of unidirectional scheduling. However, it may corrupt the data transmission in bidirectional scheduling using frequency channel unless the data packets are of same length. For example, in slot 0, node 4 is sending data to 5, node 3 is sending data to 2. If the data packet is of same length, then the ACK packets will be successfully received by node 4 and 5 respectively. Otherwise, it may occur that when node 4 is receiving ACK, node 3 is still sending the data packet, thus ACK packet is corrupted at node 4. There are two possible solutions to this problem. The first solution is to confine the application of bidirectional scheduling to a fixed length data packet in a wireless sensor network. The second solution is to alternate the flow directions of the unidirectional scheduling. It is easy to see that the second solution offers flexibility at the cost of throughput degradation.

5. PERFORMANCE EVALUATION OF NETWORKING AND SCHEDULING PROTOCOLS

As the protocols for networking and TDMA scheduling interact with each other intimately, we shall carry out one integrated simulation employing both networking and scheduling protocols. Two major indicators are important performance measures for the protocol evaluation: normalized energy consumption per bit of data transmission and aggregated throughput per node within the sensor network. For the last few years, there have been several energy efficient MAC protocols proposed for wireless sensor networks. In this research, we will compare the proposed scheduling protocols with SMAC, a well-known MAC protocol developed specifically for wireless sensor networks [3].

To carry out the simulations to evaluate the performance of the networking and scheduling protocols, we assume the cluster within a chain-type network shall have10 nodes and therefore need 9 hops from one end to the other. Data load is generated at each node and varied by changing the data arrival rate. The simulation runs 100 frames for each data load. We use energy model of Mica motes, the power consumptions of the radio in transmitting, receiving and sleeping modes are 36mW, 14.4mW and 15 μW respectively. Other important simulation parameters are listed in table 5.

Table 5: Simulation parameters

Radio bandwidth	20 kbps
RTS/CTS/ACK packet length	10 bytes
Query packet length	30 bytes
Data packet length	0~200 bytes
Frame length	1.1s
Slot_id_max	12
Duty cycle of SMAC	1%~100%
Max. and Min. collision counter	6, 3
DIFS_Time	2 bytes

Slot length is no less than the transmission time of the maximum data packet and a control packet (ACK) as well as the maximum turn-around propagation time in the network. Thus for 20kbps radio bandwidth, the frame length is designed to be 1.1s after considering all the above factors as well as the guard time. The overhead in Synchronization period and Joining period is assumed the same for both protocols and thus not considered in the simulation. In these simulations, the sensor data are not aggregated at any intermediate nodes in order to maximize the load on the MAC protocols. However, in practice, the sensor data are usually aggregated at intermediate nodes. Nevertheless, the performance of the networking and scheduling protocols will not be affected by whether or not a data aggregation scheme is implemented at the intermediate nodes.

Figure 11 demonstrates the energy efficiency of the proposed networking and scheduling protocols. The energy consumption per bit is obtained from the result of the total energy consumption of all nodes divided by the total bits successfully transmitted in the network. It shows that the proposed TDMA scheduling scheme outperforms the SMAC with duty-cycle 10% and 100% by about 27% and 40%, respectively. This is mainly because the TDMA scheduling scheme completely eliminates the collision and overhearing, and powers on the radio only when there is data to send or receive. In addition, it reduces the idle listening to a very low level by listening just DIFS_Time period (0.2ms) in its scheduled receiving slot. Furthermore, it has less overhead than SMAC. For each successfully transmitted data packet, the scheduling scheme only induces ACK overhead and Query overhead. The Query overhead is imposed to all 12 slots of a frame and in each slot there are multiple parallel transmitted data packet. In contrast, SMAC will induce RTS/CTS/ACK overhead for each single data packet, and retransmissions caused by inherent collisions will lead to extra energy waste.

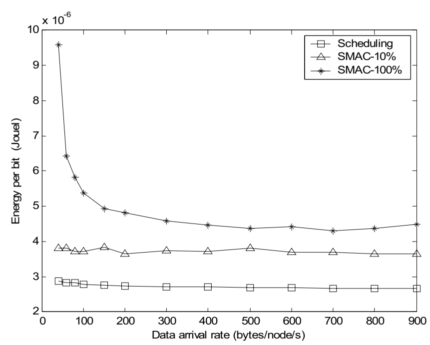

Figure 11. Energy consumption performance

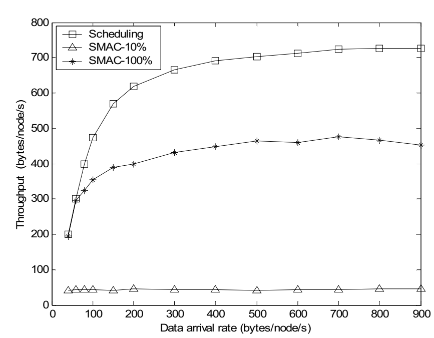

Figure 12. Aggregate throughput performance

Figure 12 shows the throughput performance represented by the result of the total bytes successfully transmitted in the network divided by the total number of nodes. It demonstrates that the throughput of the proposed TDMA scheduling is about 15 and 1.5 times that of the SMAC with duty-cycle 10% and 100% respectively, while still maintaining higher energy efficiency as shown in Figure 11. The throughput gain comes from its pipelining the maximum number of transmissions that do not interfere with each other because of chain-type topology. The gain also comes from collision-free transmission and reduced signaling overhead. When the duty-cycle of SMAC is less than 10%, the active period of a node is almost equal to or less than the time for transmitting a data packet length and therefore results in near zero throughput rates. The results for these cases are therefore not presented in Figures 11 and 12.

6. SUMMARY AND DISCUSSION

We have presented in this paper an energy efficient media access control (MAC) protocol for chain-type wireless sensor networks. The chain-type sensor networks are fundamentally different from traditional sensor networks in that the sensor nodes in this class of networks are deployed along narrow and elongated geographical areas and form a chain-type topology. In this paper, we developed novel TDMA scheduling protocols that take full advantages of the available channel reuse inherent in the chain-type sensor networks to develop energy efficient and high data throughput MAC protocols. The synchronized TDMA scheduling allows the nodes to power on only when it is scheduled to send and receive and therefore results in additional energy saving. Within a cluster, parallel transmission is made possible because of the linear distribution of nodes within the chain-type topology and this yields the desired high throughput. Preliminary simulations have been carried out to show that the proposed TDMA scheduling outperforms the well-known SMAC scheme in terms of energy efficiency and data throughput under various duty cycles.

To develop a complete suite of protocols and algorithms for the chain-type sensor networks, appropriate data aggregation schemes also need to be developed. Data aggregation plays important roles in sensor networks since sensor data are inherently correlated due to sense deployment of the sensor nodes. Additional energy saving can be achieved with well designed data aggregation schemes. We are currently working on a unique data aggregation scheme specifically designed for the chain-type wireless sensor networks.

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